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MECHANICAL AND MICROSTRUCTURAL CHARACTERIZATION OF DUCTILE IRON PRODUCED FROM FUEL - FIRED ROTARY FURNACE

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ABSTRACT

The work compared the mechanical and microstructural properties of ductile iron produced in a locally manufactured fuel- fired rotary furnace with ASTM A 536 65-45-12, with a view to standardizing the produced ductile iron. Sets of low alloyed ductile iron were produced in form of keel Y-block inside green sand mould, using a rotary furnace of 100 kg capacity. The base alloy was treated with 5.5 wt. % Mg-Fe-Si alloy for spheroidisation followed by post inoculation with 75 wt. % Fe-Si. The samples of the as-cast were machined to mechanical test samples of tensile, yield and hardness. The microstructural and mechanical characterizations of the samples were carried out using computerized Instron Electromechanical Testing Machine (Model 3369), Mansato Tensometer (Model W) and Nikon Eclipse metallurgical microscope, Scanning Electron Microscope (SEM) and X-ray diffraction (XRD) method. The results showed that the yield and tensile strength of the produced ductile iron were 367 and 540 MPa respectively with the hardness value of 185 BHN. The results obtained were compared with standard ASTM A 536 65-45-12 to confirm the suitability of the manufactured fuel-fired rotary furnace for the production of ductile iron.

Keywords: Ductile iron, Rotary furnace, Spheroidisation, Material characterization, Metallurgy.

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1. INTRODUCTION

In the last half century, the search for ferrous materials with significantly better machinability, high strength, good ductility, marked reduction in tool wear and cost has been centered on cast iron. More so, cast iron, thought to be yesterday's material is brittle, and regarded as a replacement for high-grade alloy steels and niche aluminum alloys [1]. Ductile iron (DI), also known as nodular or spheroidal graphite cast iron (SGI) is cast iron in which the graphite is present as tiny spheres (nodules) instead of the rather 'weak' flaky form in gray cast iron. Cast iron containing nodular graphite is much stronger and more ductile than gray iron of similar composition [2-10].

The advantages of ductile iron are numerous and include; easy- versatility and higher performance at lower cost. Other members of the ferrous casting family may have individual properties which might make them the choice material in some applications, but none have the versatility of ductile iron, which often provides the designer with the best combination of overall properties [11-14]. This versatility is especially evident in the area of mechanical properties where ductile iron offers the designer the option of choosing high ductility, with grades guaranteeing more than 18% elongation, or high strength, with tensile strengths exceeding 826 MPa [4]. Ductile irons possess good hardness and good wear resistance, good corrosion resistance, high tensile and yield strength that vary widely across the various grades. It has strength, impact toughness, and ductility comparable with those of many grades of steels, while exceeding by far those of standard gray irons. It has the same advantages of design flexibility and low cost casting procedures of gray irons [6]. In addition, they have compressive strengths (that can be utilized more widely than tensile strengths), with values about twice the tensile strength. Impact strengths are better than in gray irons, with lower grades approaching values common for mild steel. The fatigue strengths are approximately 40 to 50% of the tensile strengths. While the electrical resistivity are significantly lower compared to grey cast irons. Ductile iron corrosion resistance is similar to those of grey iron. Machinability is dependent on hardness, with ferritic grades machining better than others [15]. Graphite contributes to machinability because it acts as a lubricant during cutting and also tends to break up chips. Like gray iron, ductile iron has inherent corrosion resistance. In addition, the spheroidal graphite has desirable lubricating and crack arresting effects in system [4]. The use of most common grades of DI "-as-cast-" eliminates heat treatment costs, offering a further advantage. It is well known that the presence of graphite contributes directly to lubrication of rubbing surfaces and provides reservoirs to accommodate and hold lubricants. This means good resistance to mechanical wear [16-18]. These advantages of ductile iron increased its use for different engineering applications, therefore increasing local production of the iron.

Although melting is carried out with a high degree of success in industry and research institutes in developed countries, where sophisticated but often proprietary and /or patented processes and operations are in use, there have been reported cases of poor performance of locally made fuel- fired melting furnaces in developing countries [19]. Induction and electric arc furnaces are not adequately available in some developing countries especially Nigeria, due to cost of procurement, maintenance required from time to time and the challenge of inadequate power supply [20]. Rotary furnace is a typical example of fuel-fired furnace, characterized by ease and low cost of operation, fuel economy, low cost of manufacture, high thermal efficiency and low maintenance [21]. Rotary furnace of 100kg to 300kg capacity have been designed and built at Engineering Development Institute (EMDI), Akure and Prototype Engineering Development Institute, Ilesa, as a way of providing one of the most important missing links in the metal producing technology and building capacity in the foundry industries [22].

Adeyemi *et al.,* 2014 produced a set of ductile irons using an indigenously manufactured rotary furnace, the '-as-cast'- samples were subjected to the Hilger Analytica atomic mass absorption spectrometer for chemical composition analysis. The results obtained showed the average percentages of carbon, silicon, manganese, magnesium, sulphur and phosphorus values as 3.60, 2.00, 0.30, 0.50, 0.01 and 0.04 respectively [20]. Furnace is a term used to identify a closed space where heat is applied to a body in order to raise its temperature [23-25]. Local foundries have been using indigenously manufactured rotary furnace for production of ductile iron in Nigeria, although the produced ductile irons have been characterized, yet not standardized. This study characterized and standardized ductile iron produced from an indigenous rotary furnace to confirm the suitability of the furnace for its production by comparing the results with the ASTM standard and results obtained using standard induction furnace.

2. MATERIALS AND METHOD

The ductile iron was produced by sand casting process. The charge make-up consisted mainly of pig iron, steel scrap, ferroalloys and returned ductile iron scrap, all of 50 kg. The charge make-up was melted using indigenous rotary furnace of 100 kg capacity and sandwich spheroidisation treatment. The base alloy was treated with 5.5 wt. % Mg-Fe-Si alloy for spheroidisation, followed by post inoculation with 75 wt. % Fe-Si. Thereafter the materials were cast in the form of keel Y-blocks inside the green sand mould according to the ASTM A897M-90. The chemical analysis of the produced ductile iron was carried out using spectrometer EDX 3600B. Some mechanical properties such as tensile, hardness and yield tests were carried out on the produced ductile iron using computerized Instron Electromechanical Testing Machine (Model 3369), Mansato Tensometer (Model W) and Avery Dension Fatigue Testing Machine (Model 7305) respectively. The microstructure characterization of the produced ductile iron was done using a Nikon Eclipse metallurgical microscope, Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD) method

The results obtained were compared with American Society of Testing and Materials (ASTM A536 65-45-12) standard. Table 1 presents the standards for mechanical properties, chemical composition and microstructure of ductile iron according to ASTM A536 65-45-12.

Table 1 Chemical, mechanical and matrix structure requirements of ASTM A536 65-45-12 ductile iron castings

Chemical Requirements		Mechanical Property Requirements	
Elements	Composition (%)	Properties	Requirement
C	3.50- 4.00	Ultimate Tensile Strength	≥448 MPa (65,000psi)
Si	2.20- 2.90	Yield Strength	≥310 MPa (45,000 psi)
Mn	0.30- 0.60	% Elongation in 50mm	≥10% (ASTM A536≥ 12%)
P	0.050 Max	Hardness	156-217 BHN
S	0.025 Max		
Mg	0.02- 0.06	Matrix Structure Consider nodular graphite in a matrix of Ferrite. The microstructure consists of Types I &II nodular graphite as defined in ASTM A247. The matrix is	

		ferrite with approximately 5-25% pearlite. The rim will have a higher nodular count and will be mostly ferrite. Chill carbides will be less than 5% in any field at 100 X and will be well dispersed.	

3. RESULTS AND DISCUSSION

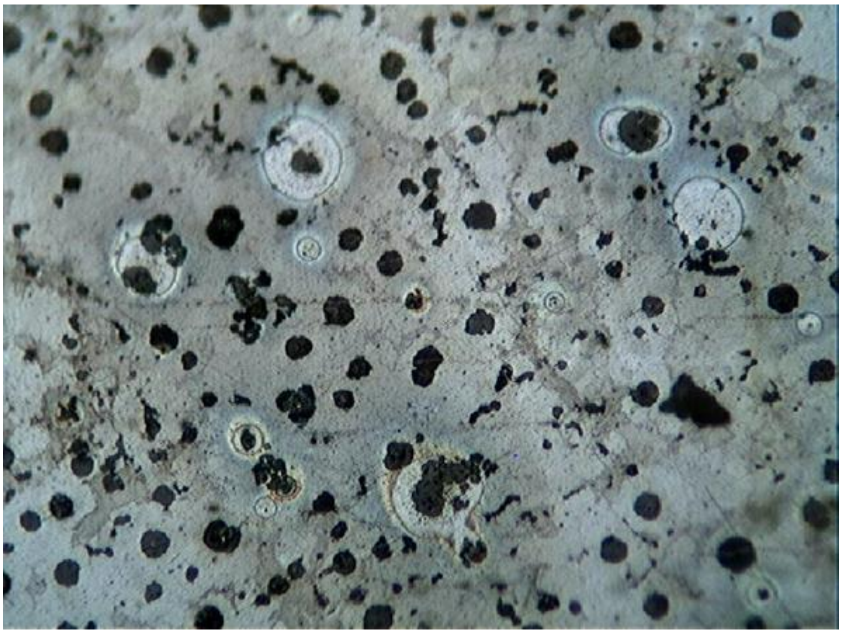
The results of the chemical analysis of the produced ductile iron by EDX 3600D spectrometer expressed in mass content of alloying elements are presented in Table 2. The micrographs of the as-cast ductile iron viewed under metallurgical microscope are presented in Figure 1. The microstructure of the unetched sample shows predominantly ferritic matrix with graphite nodules dispersed in it. The etched sample shows bull's eye structure with ferrite surrounding the graphite nodules dispersed in it. The SEM image and electron dispersive X- ray (EDX) analyses of as- cast ductile iron (Figures 2– 4) indicate that the as cast iron is ductile iron. Spectra 1 and 3 show ferrite matrix with predominant iron peaks and spectrum 2 shows graphite nodule with predominant carbon peaks. The XRD pattern of the produced ductile iron is as presented in Figure 5 which confirmed that the as-cast iron is ductile iron. From the profile pattern, ferrite (α) phase was observed on (110) plane at 2θ of 45.0443° and intensity 100, (200) plane at 2θ of 65.2481° and intensity of 100, and 82.4463° and intensity of 100. The results of the mechanical properties of produced DI as compared with standard ASTM A 536 65-45-12 are presented in Tables 1 and 3, and also Figure 4.

Table 2 Chemical composition of produced ductile iron

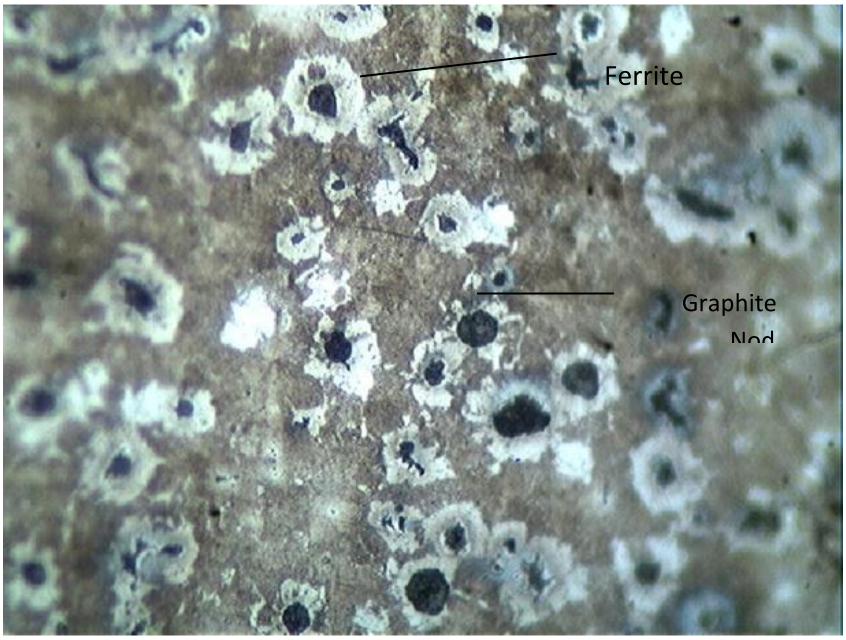
Element	C	Si	Mn	P	S	Cu	Cr	Mo	Ni	Mg	V	Ti	Al	Sn	Co	Nb	Fe
Composition (%)	3.620	2.550	0.400	0.017	0.018	0.017	0.048	0.003	0.012	0.030	0.014	0.072	0.015	0.004	0.001	0.001	Bal.

It can be seen from Table 2 that percentage carbon, silicon, manganese, phosphorous, sulphur and magnesium compositions; (3.62, 2.55, 0.40, 0.017, 0.018 and 0.03 %) were within the range of ASTM A536 65-45-12 standard as shown in Table 1. The recommended maximum percentage of phosphorus and sulphur contents for ASTM A 536 65-45-12 were 0.05 and 0.025% respectively as compared with 0.017 and 0.018% in the produced ductile iron. The result was also within the range of the percentage chemical composition of ductile iron produced by Adeyemi *et al.,* 2014 using another indigenously manufactured rotary furnace. The microstructure contained nodular graphite in a matrix of ferrite (Figure 1). The characteristic 'bulleye' features in the microstructure of the produced ductile iron compared favourably with standard ductile iron according to ASM handbook. This microstructure agreed with the study of Adeyemi *et al.,* 2014.

The chemical composition, mechanical properties and the matrix structure of as-cast ductile iron conform to ASTM A536 grade 65-45-12 (Tables 1 and 3). Both the yield strength and the tensile strength are higher than 310 MPa and 448 MPa which are the least requirements of the standard respectively (Table 3). The hardness of the produced ductile iron is 185 BHN which is within the range of 156 -217 BHN according to ASTM A536 grade 65-45-12.

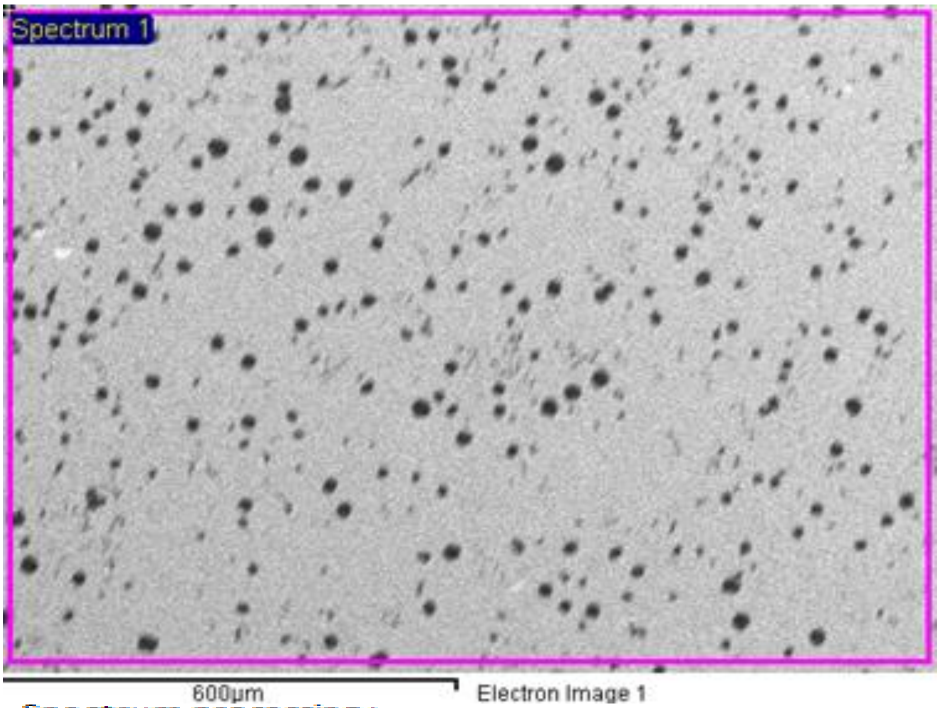


(a)



(b)

Figure 1 Microstructure of the as-cast ductile iron (a) un-etched optical micrograph (b) 2 % Nital etched optical micrograph



Spectrum processing :

No peaks omitted

Element	Weight%	Atomic%
C K	19.04	51.52
Si K	2.39	2.76
Fe K	78.57	45.72
Totals	100.00	

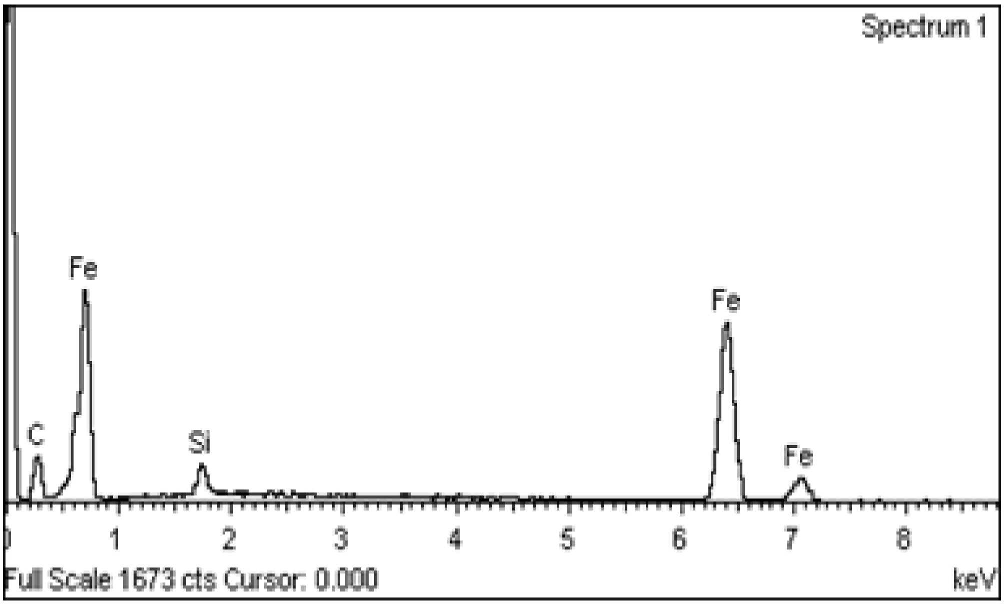
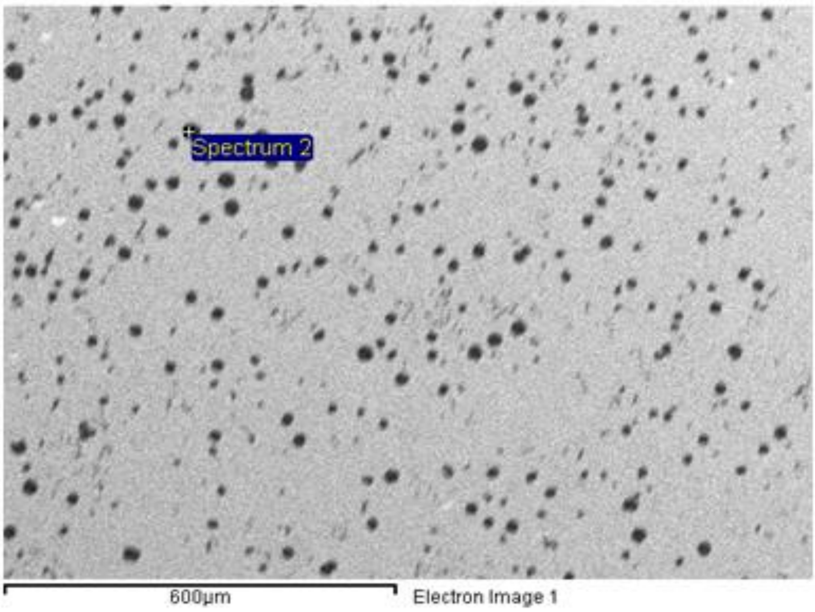


Figure 2 SEM image and EDX analyses of as-cast ductile iron Spectrum 1



Element	Weight%	Atomic%
C K	98.87	99.75
Fe K	1.13	0.25
Totals	100.00	

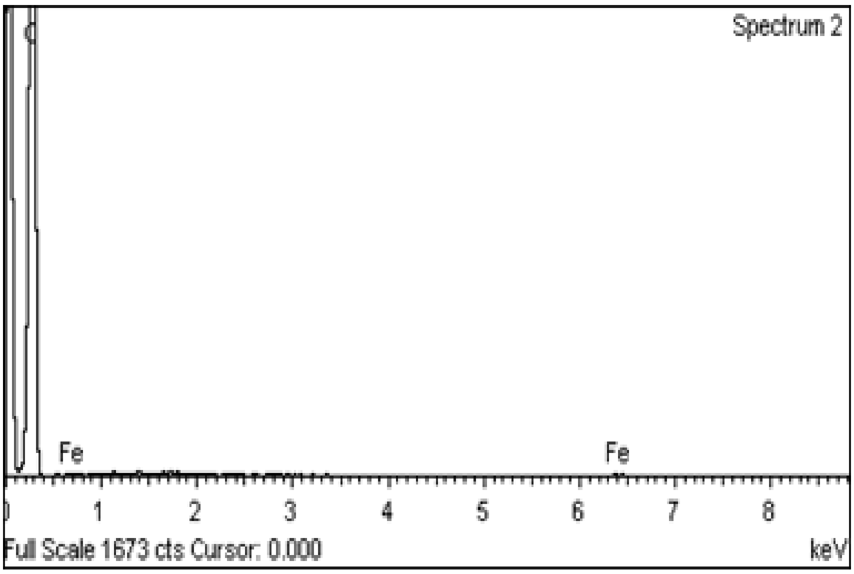
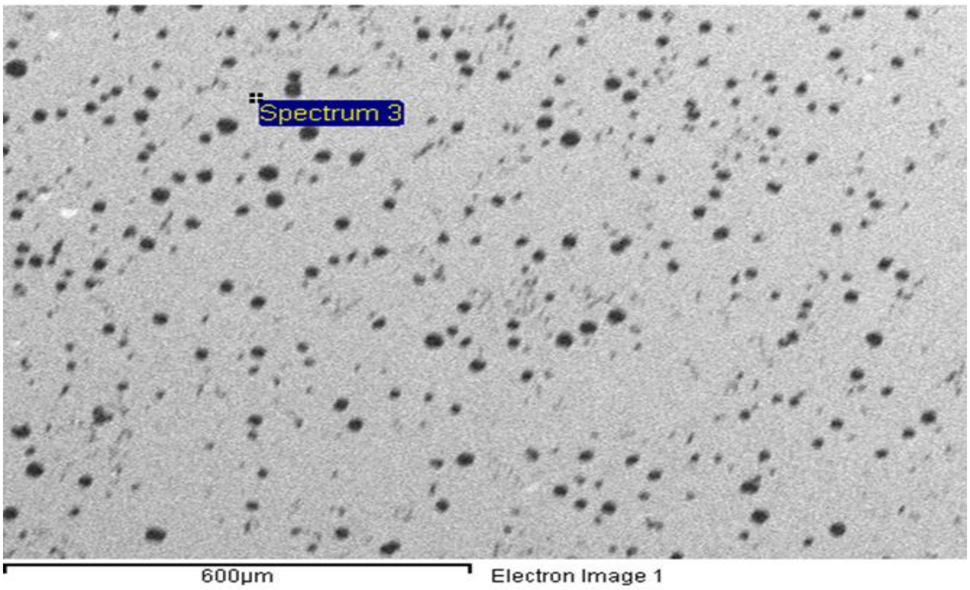


Figure 3 SEM image and EDX analyses of as-cast ductile iron Spectrum 2



Spectrum processing :

No peaks omitted

Element	Weight%	Atomic%
C K	5.15	19.66
Si K	3.00	4.90
Fe K	91.85	75.44
Totals	100.00	

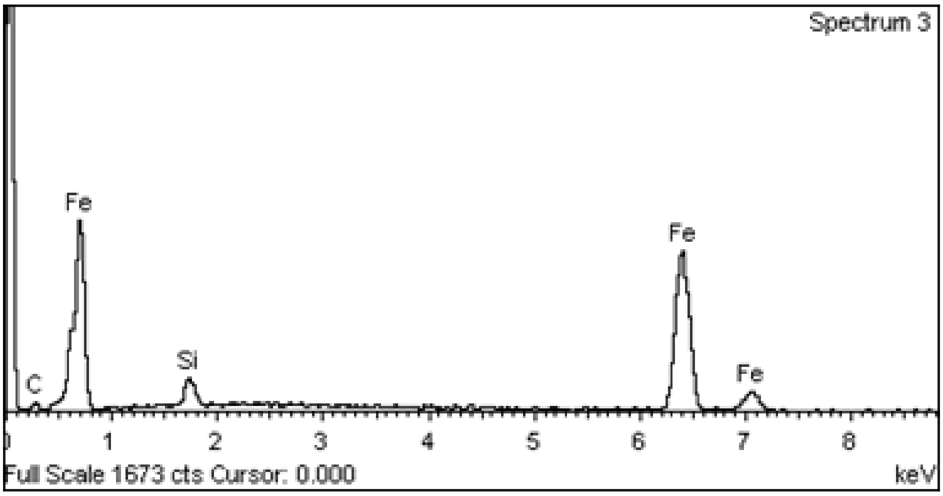


Figure 4 SEM image and EDX analyses of as-cast ductile Spectrum 3

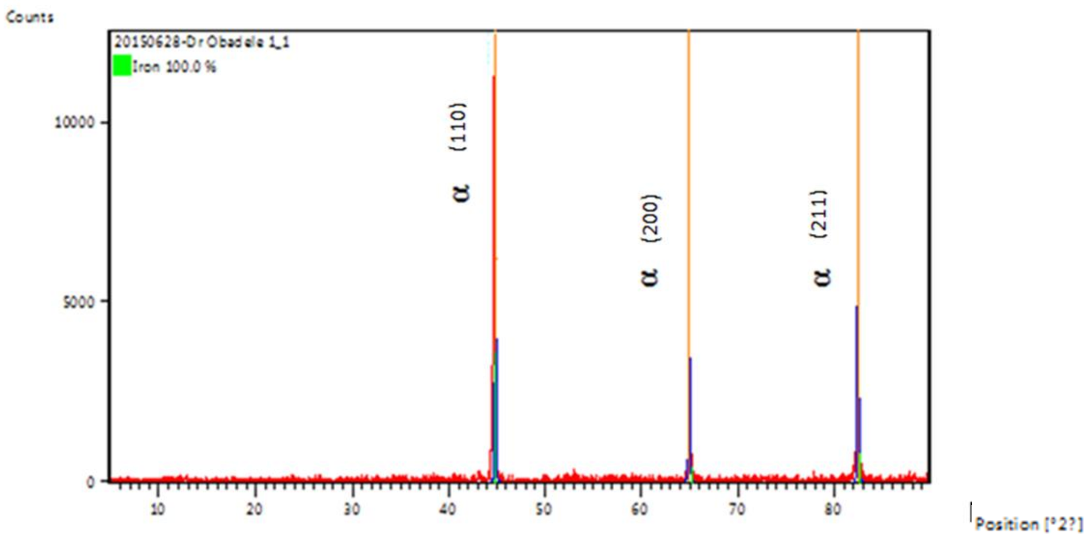
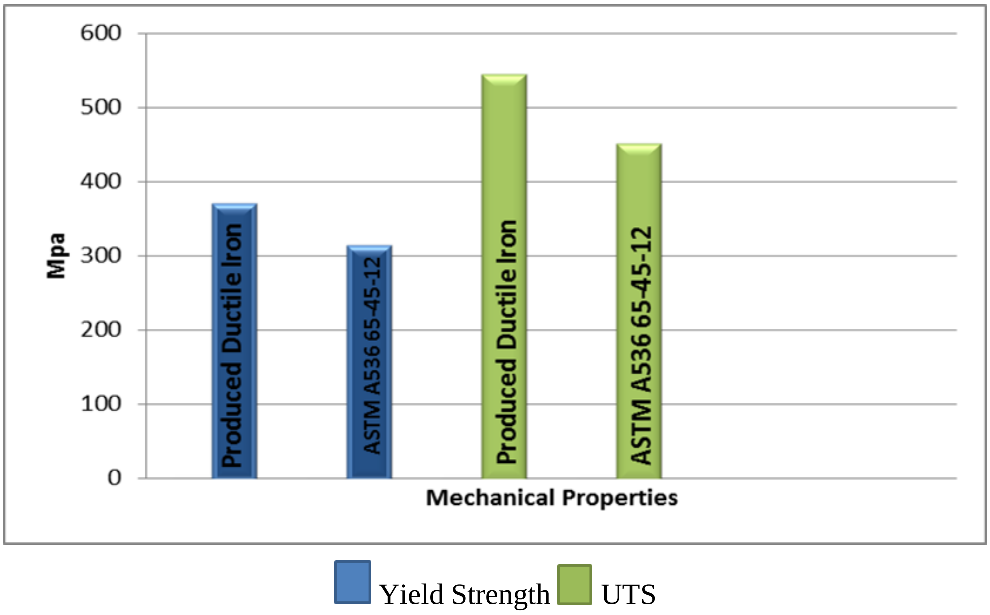


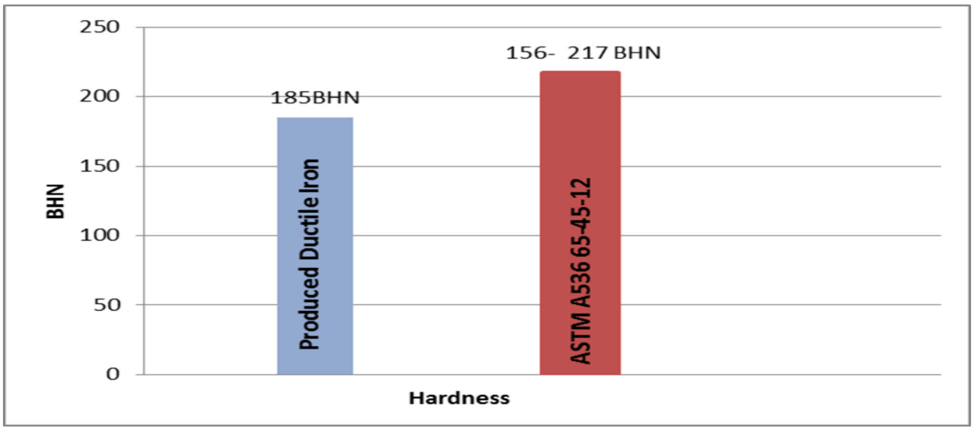
Figure 5 XRD pattern of ductile iron

Table 3 Results of Mechanical Testing on as cast ductile iron

Mechanical Properties	Yield Strength (MPa)	Tensile Strength (MPa)	Hardness (BHN)	Fatigue (MPa)
Ductile Iron	367	540	185	243.0



(a)



(b)

Figure 6 (a) Comparison of Yield strength and Ultimate Tensile Strength of as-cast Ductile Iron with ASTM A 536 65-45-12 iron (b) Comparison of Hardness properties of as-cast Ductile Iron with ASTM A 536 65-45-12 iron

4. CONCLUSION

The purpose of this research was to characterize the ductile iron produced in indigenously manufactured rotary furnace to confirm it suitability for the production. The locally fabricated rotary furnace is capable of producing ductile iron that conforms to ASTM A536 grade 65-45-12. The DI produced in the locally fabricated rotary furnace can be used in Nigeria for standard construction work as a result of this work.

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